The Johns Hopkins University

The Reflecting Power of Metals in the Ultra-Violet Region of the Spectrum

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

EDWARD O. HULBURT

June 2, 1915

Diss.
Baltimore
1915.

45453

The Johns Hopkins University

The Reflecting Power of Metals in the Ultra-Violet Region of the Spectrum

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

R. UNIV. BIBLIOTHEEK LEIDEN

BY

EDWARD O. HULBURT

June 2, 1915

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XLII OCTOBER 1915 NUMBER 3

THE REFLECTING POWER OF METALS IN THE ULTRA-VIOLET REGION OF THE SPECTRUM

By E. O. HULBURT

INTRODUCTION

Knowledge of the reflecting power of metals in the ultra-violet region of the spectrum is far from complete. It was the purpose of the present investigation to extend as far as possible into the region of shorter wave-lengths the curves of reflecting power for metals, and thus to obtain data which might be of service in designing apparatus for use in ultra-violet work, and which might also possess theoretical value. In the present work the reflecting powers of metals, for an angle of incidence of 18°, have been measured throughout the region 3800 to 1800 A by a direct method.

HISTORICAL

In 1902 Hagen and Rubens[1] published the results of their measurements on six of the more common metals—silver, gold, platinum, copper, nickel, steel—and on four alloys, in which the curves of reflecting power were carried out as far as wave-length 2500 A. The method used was a direct one, and consisted in

[1] *Annalen der Physik*, 1, 352, 1900; 8, 1, 1902.

observing the incident and reflected intensities of a monochromatic beam of light by means of a sensitive thermo-couple. Their table has stood as the final word on the subject.

Beyond wave-length 2500 A there have been within the knowledge of the present writer no direct determinations at all of the reflecting power of any substance.

In 1903 Minor[1] made katoptric measurements on four metals—copper, steel, cobalt, and silver. He used a photographic method, and was able to get measurements for two points beyond 2500 A, namely, at 2313 and 2265 A. The reflecting powers were calculated by means of Drude's well-known formula connecting the reflecting power, the refractive index, and the absorption coefficient of the metal.

In 1910 Meier,[2] using a method similar to that employed by Minor, determined the reflecting powers from katoptric measurements down to wave-length 2500 A for gold, nickel, iron, platinum, bismuth, zinc, selenium, and for several alloys.

The results of these three investigations comprise our total knowledge on this subject, for the observations of other experimenters have contributed nothing new.

METHOD

The principle of the method employed in the present investigation was very simple. Light from a source rich in ultra-violet light was resolved into a spectrum, and a small, nearly monochromatic, beam was isolated by the slit B, Fig. 1, of the spectrograph, and passed into the metal chamber shown in Fig. 1. The intensity of the direct beam was measured by a photo-electric cell F connected with an electrometer. The intensity of the beam when reflected was measured by the same cell. This was effected by swinging both the cell and the mirror from their original positions M and F to the new positions M' and F' respectively. The length of the optical path from the slit to the cell was kept constant for the two positions. Consequently the ratio of the two measurements gave the reflecting power of the mirror.

[1] *Annalen der Physik*, 10, 581, 1903. [2] *Ibid.*, 31, 1017, 1910.

APPARATUS

The spectrograph.—This consisted of the usual Rowland mounting of a very fine concave speculum metal reflecting grating (*C*, Fig. 1) of 50 cm focal length. The grating had a ruled surface 6×9 cm, and was ruled in this laboratory especially for the purpose of this investigation. Slit *A*, Fig. 1, back of which the source of light was placed, was fixed on a movable brass arm *CD*. This arm was constrained to move by a pin through a slot at end *C*, and a pivoted slot underneath *A* sliding on a curved brass track *BA*, so

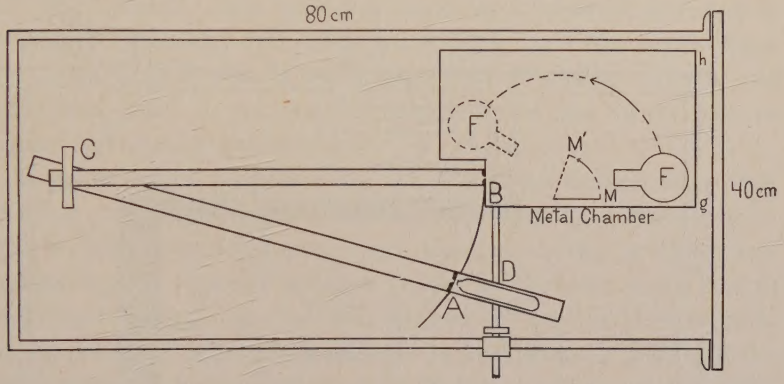

FIG. 1.—Horizontal plan of spectrograph

that slit *A* moved on the circumference of the circle whose diameter is *CB*. *CB* was 50 cm in length. Underneath the brass arm *AC* at *D* was a nut which worked without play on a steel screw (24 threads to the inch); by turning this screw the brass arm holding the slit *A* could be moved, thus allowing various wave-lengths to pass through slit *B*. Wave-lengths could be recorded by this apparatus throughout the region from 3800 to 1000 A.

The grating was ruled 15,000 lines to the inch by a diamond point so selected that the first-order spectrum on one side was very bright, and this bright first order was used throughout the present work. The spectrum, brought to a focus at slit *B*, was normal, and the dispersion of the grating was such that with slit *B* 0.5 mm wide a beam containing a wave-length range of 16 A passed through. In the present work slit *A* and slit *B* were both 0.5 mm wide.

The source.—An end-on hydrogen discharge tube, such as is described by Lyman,[1] was employed as the source of light. The tube was of the internal capillary type, equipped with a fluorite window and filled with hydrogen at about 1.5 mm of mercury pressure. This was excited by a 1100-volt transformer taking from 0.5 to 1.5 amperes in the primary, run on 60-cycle, 110-volt, alternating current. This tube, painted black, and wrapped with

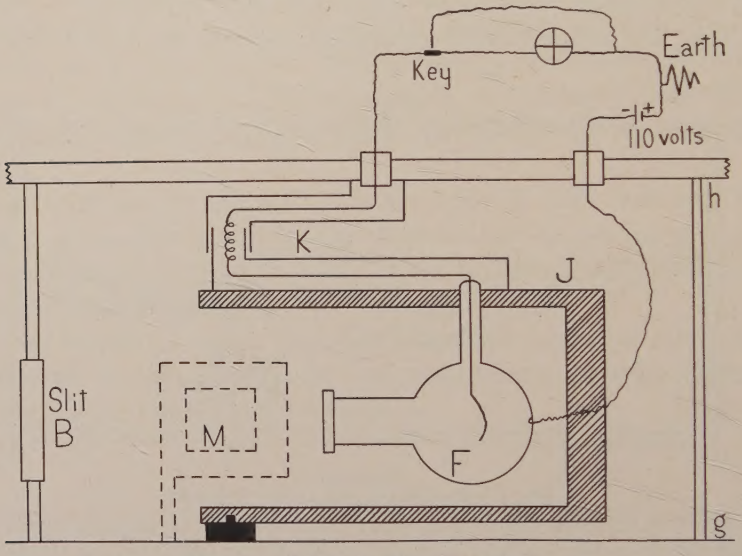

FIG. 2.—Metal chamber (elevation)

tin-foil radiators to keep it cool, was clamped in position back of slit A.

The photometer.—The light from the hydrogen tube was brought to a focus at slit *B*, and then passed into the metal chamber shown in horizontal section in Fig. 1 and in vertical section in Fig. 2. Inside this compartment was placed a photo-electric cell *F*, which, when connected with the electrometer, measured the intensities of the incident and reflected beams of light. The metal chamber, from which the end *hg* could be removed, served, when closed, to screen the photo-electric cell from all light, except the beam coming through slit *B*, and also to protect the cell and connections from

[1] *Astrophysical Journal*, **23**, 181, 1906.

electrostatic disturbances. The cell was supported in a brass frame J, rotating around a vertical axis. A second frame M (shown in dotted lines in Fig. 2) served as a support for the metal mirror. The mirror frame and the photo-electric cell frame were connected by a spring, so that when the cell was swung from F to F' the mirror swung from M to M' (Fig. 1). This whole shift could be made from the outside. The distance from the slit B to the mirror was 5 cm, and a mirror surface 4×2 mm was large enough to reflect a cone of light of sufficient size to completely cover the window of the cell at F'. The photometer consisted of the photo-electric cell and electrometer. The spectrum from the hydrogen tube was of very small intensity, even when the grating used was one of such short focal length and of such large area of ruling. Hence the instrument used to measure the intensity of the beam had to possess the utmost sensitiveness.

A cell in which sodium is the active metal is known to be very sensitive, and accordingly a method of preparing sodium photo-electric cells was developed,[1] and the cell finally selected was equipped with a fluorite window 14 mm in diameter and 1 mm in thickness. This sodium cell was wrapped in tin foil and placed in the supporting frame. The wire to the electrometer led from the cell through the jointed copper tube K, Fig. 2, out through sulphur supports to the earthing key, and thence to the electrometer. The electrical connections are shown in Fig. 2. The earthing key was merely a pointed brass rod touching a small brass plate, both made of the same piece of brass and filed bright. This gave no trouble with contact difference of potential. This type of key is, in the author's experience, much better than any mercury or electrolyte key, requiring absolutely no attention after it is once made, and giving complete satisfaction even for the most delicate work.

The electrometer was a Dolezalek quadrant electrometer with an aluminum needle. The needle was suspended by a quartz fiber rendered conducting by a slight coating of platinum put on by cathode sputtering, and was charged to 110 volts from a constant potential storage battery. In this work the electrometer had a sensibility of 3300 mm per volt difference of potential between the

[1] Hulburt, *Astrophysical Journal*, 41, 400, 1915.

quadrants (the deflections being observed on a scale four meters distant), and in this case the needle had a free period of 21 seconds. The electrometer and the wire leading to the photo-electric cell were inclosed in metallic shielding made air-tight.

Through the kindness of Dr. E. Karrer, of the United Gas Improvement Company of Philadelphia, the writer secured the use of a potassium photo-electric cell which proved of the greatest service in the preliminary setting up of this apparatus.

In taking observations it was found most convenient to use the steady-deflection method, rather than a rate-of-drift method. The procedure was as follows: The connection to earth was broken, and the reading of the position of the electrometer needle recorded; then the hydrogen tube was turned on for a convenient length of time, e.g., 15 seconds, and the reading taken again after the needle had come to rest. If there was a natural drift of the needle—i.e., a drift when the cell was in the dark—the final reading was taken one minute after the first reading and the drift during the interval subtracted. During the course of the work there were times when the drift was zero and times when it amounted to as much as 10 mm per minute. The exact cause of the drift was not found, but the drift always increased with a rise in temperature of the room; probably this rise in temperature augmented the natural ionization of the air, and doubtless also produced effects in the photo-electric cell. The current through the hydrogen tube and the time of exposure were adjusted to produce deflections of convenient size; whenever possible, deflections for the direct beam of 100 to 200 mm were used.

The intensity of the light from the hydrogen tube fluctuated from day to day, but remained very constant for shorter periods of time. The changes in intensity were occasioned by changes in pressure inside the hydrogen tube, which were produced by the absorption and evolution of gases by the electrodes. Also the tube became gradually weaker and weaker in the region from 2500 A down. This was due to a film being formed on the inside of the fluorite window by the discharge; this film was invisible, but upon cleaning the window and refilling the tube with hydrogen the original power of the tube was regained. However, a single tube was useful for a month.

The sensibility of the photo-electric cell did not change perceptibly in several months, and since at all times the intensity of the light falling on the cell was very feeble, no evidences of photo-electric fatigue were ever observed.

Measurements made with this apparatus on a polished quartz surface gave values of the reflecting power which agreed within the experimental error with the calculated values. Also the agreement with the results of other observers is satisfactory. Single observations varied by as much as 7 per cent, so the final values recorded in the work are the means of from two to six measurements. It is considered that the final values are correct to two parts in one hundred for reflecting powers above 25 per cent, the error increasing for lower values of the reflecting power.

RESULTS

The results are given in the form of curves, Figs. 3–7. The curves are plotted with the reflecting powers as ordinates and the wave-lengths in Ångström units as abscissae. The reflecting powers, for an 18° angle of incidence, were measured at intervals of about 60 A. In all cases where it is possible, comparison tables are given between the values for the reflecting powers determined by other workers and the values given in this paper; but it is to be noted that the reflecting powers found by others are for an angle of incidence 1–2°, or for normal incidence (when the reflecting power is calculated from katoptric measurements), whereas the values found in this work are all for an 18° angle of incidence.

Aluminum (Fig. 6).—Brilliant cathodic films of aluminum were produced by sputtering on glass from a freshly scraped aluminum cathode in an atmosphere of mercury vapor. It required about three hours to deposit an opaque layer of the metal. The curve is for an opaque film of aluminum. It is interesting to note that, with the exception of silicon surfaces, these films were the most efficient ultra-violet reflectors found.

Antimony (Fig. 4).—The mirror of Curve II was a cathodically deposited mirror from the Bureau of Standards, and although nearly free from imperfections, it did not seem as white as the aspect of the crystals of the metal would seem to indicate.

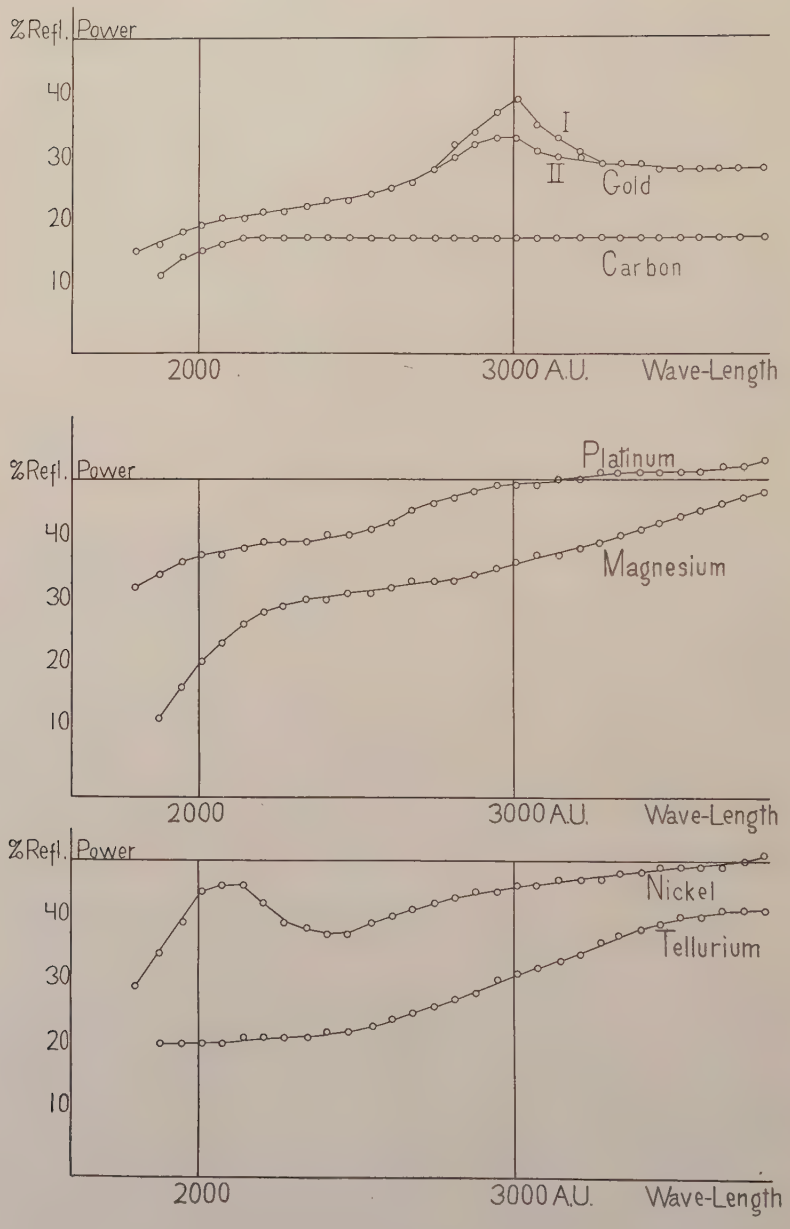
% Refl. Power
40
30
20
10
I
II
Gold
Carbon
2000
3000 A.U.
Wave-Length
% Refl. Power
Platinum
Magnesium
40
30
20
10
2000
3000 A.U.
Wave-Length
% Refl. Power
Nickel
Tellurium
40
30
20
10
2000
3000 A.U.
Wave-Length

FIG. 3

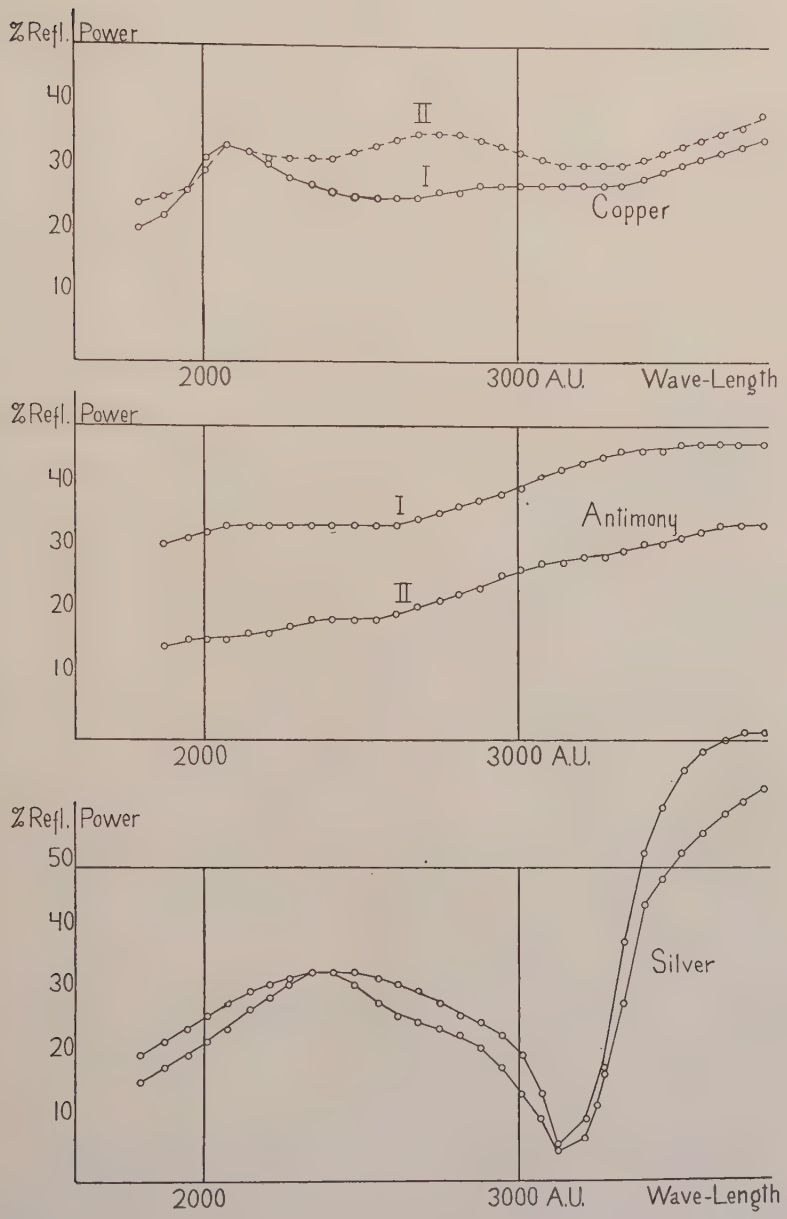
% Refl. Power
40
30
20
10
II
I
Copper
2000
3000 A.U.
Wave-Length
% Refl. Power
40
30
20
10
I
Antimony
II
2000
3000 A.U.
% Refl. Power
50
40
30
20
10
Silver
2000
3000 A.U.
Wave-Length

FIG. 4

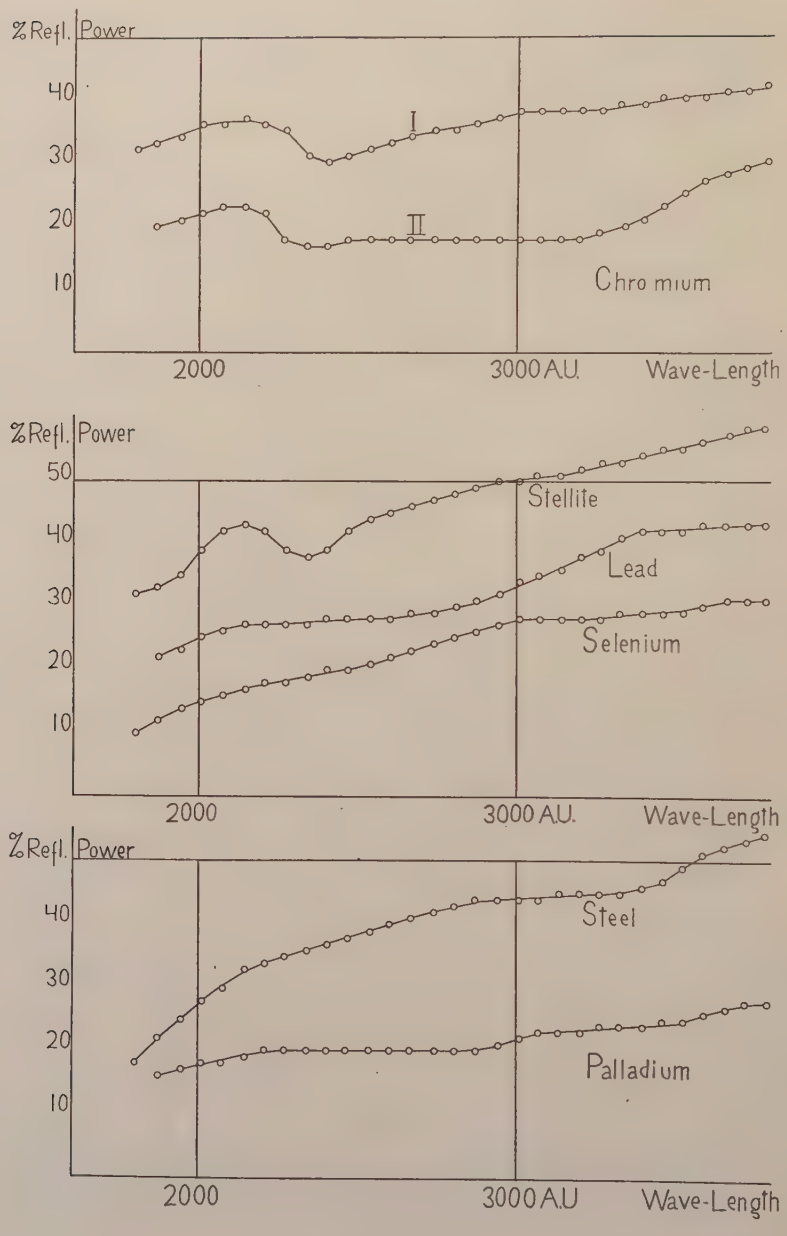
% Refl. Power
40
30
20
10
I
II
Chro mium
2000
3000 A.U.
Wave-Length
% Refl. Power
50
40
30
20
10
Stellite
Lead
Selenium
2000
3000 A.U.
Wave-Length
% Refl. Power
40
30
20
10
Steel
Palladium
2000
3000 A.U
Wave-Length

FIG. 5

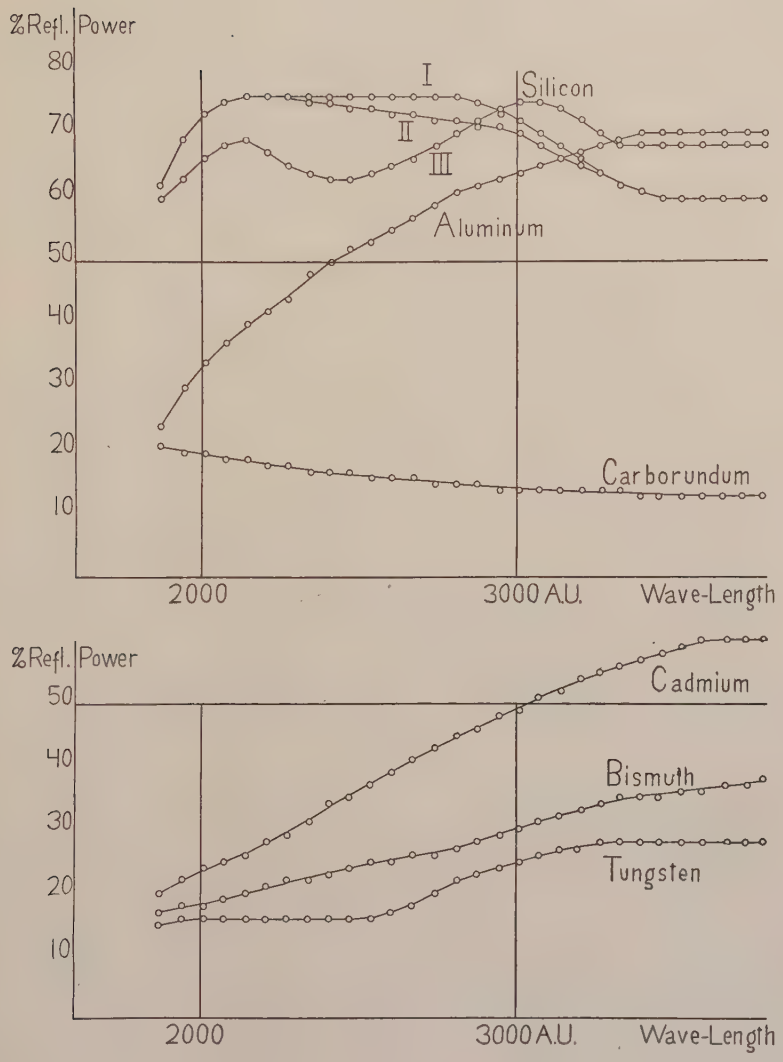

FIG. 6

A freshly split cleavage surface of a crystal, not perfect, however, but crossed by many cracks and crevices, resulted in Curve I. This did not deteriorate appreciably after standing for three weeks.

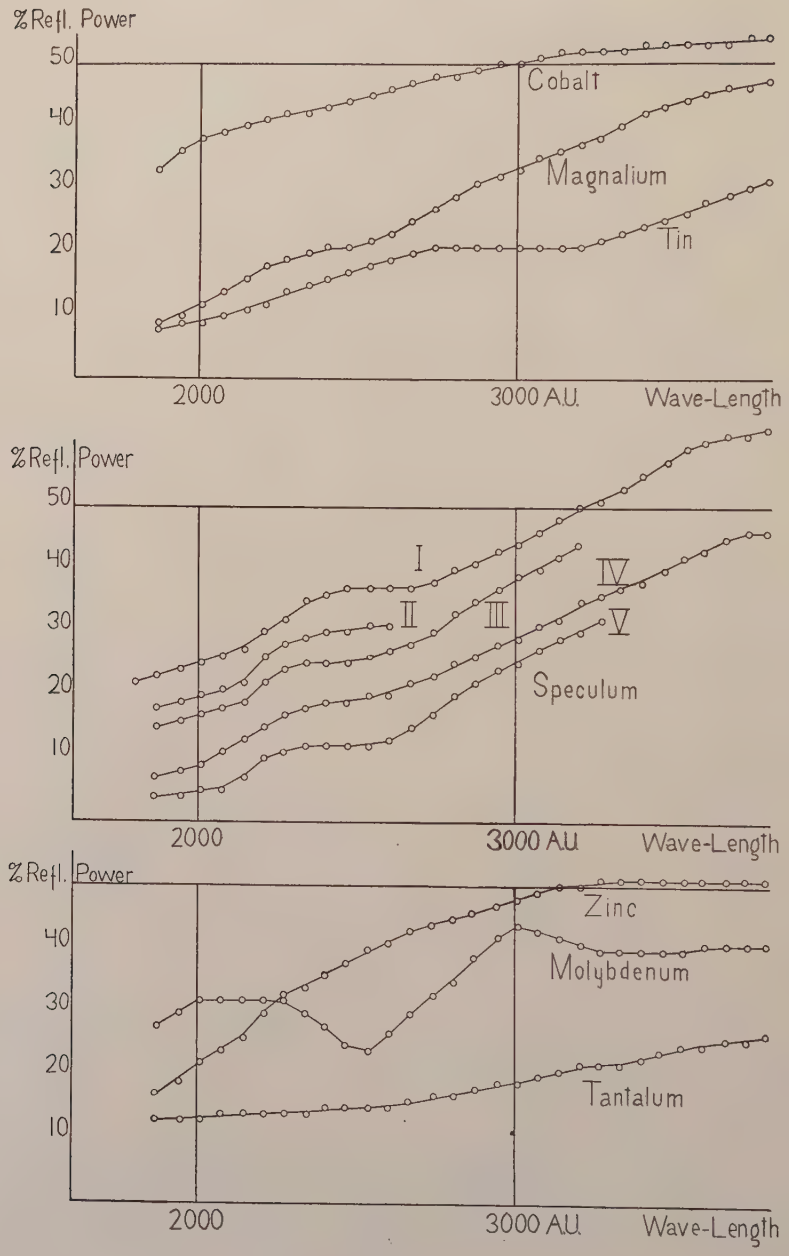
% Refl. Power
50
40
30
20
10
Cobalt
Magnalium
Tin
2000
3000 A.U.
Wave-Length
% Refl. Power
50
40
30
20
10
I
II
III
IV
V
Speculum
2000
3000 A.U.
Wave-Length
% Refl. Power
40
30
20
10
Zinc
Molybdenum
Tantalum
2000
3000 A.U.
Wave-Length

FIG. 7

Bismuth (Fig. 6).—This metal was found to sputter readily. The brightest surfaces were obtained when the deposition took place in an atmosphere of hydrogen. The curve is for an opaque film. Table I shows the comparison with results obtained by another observer.

TABLE I

REFLECTING POWER OF BISMUTH

Wave-Length	Meier Polished Plate	E. O. H. Cathodic
2573	20.1	25
2749	24.8	26
2981	31.2	29
3255	36.0	34
3611	42.5	36

Cadmium (Fig. 6).—This is a very white, soft metal and yielded bright films when sputtered cathodically in an atmosphere of hydrogen. Care had to be taken, as in the case of chromium, not to run the discharge too long at a time; for the yellow oxide very readily made its appearance, spoiling the deposit. The film was found to come down very quickly, a half-hour discharge being sufficient to produce opaque surfaces. These deposits were bright, but very soft; even brushing with a powder-puff produced scratches.

Carbon (Fig. 3).—Sputtering for four days from a piece of pure graphite produced a thin film of carbon slightly more opaque than the chromium film of Curve II (see chromium). In view of the fact that silicon possesses such remarkable reflecting properties in the ultra-violet, carbon, which is its near neighbor in the periodic system and which possesses similar electrical properties, might also be expected to show a high reflecting power in this same region. It is seen from the curve that the reflecting power of this carbon film is very low.

Carborundum (Fig. 6).—A perfect surface of a crystal was measured without further polishing. It was hoped that on account of its relation to silicon the carborundum might show peculiar reflecting properties. However, the curve for carborundum is of the same character as the curve for any dielectric, such as quartz. The

value of the reflecting power, 20 per cent at 2000 A, indicates a very high value of the refractive index.

Chromium (Fig. 5).—This metal is very white and is known to possess a high reflecting power in the visible region of the spectrum. It does not tarnish in air, and is not acted on by the ordinary reagents. Metallic chromium at present cannot be obtained free from small holes, and it was thought that cathodic films of this metal would be very serviceable, if they could be prepared.

The results are rather disappointing. Curve I is for an opaque film of chromium deposited cathodically on glass. The film was bright and free from imperfections, but showed a slight brownish tinge, which was undoubtedly due to traces of some impurity, probably the oxide or carbon. Curve II is for an extremely thin film, which, however, did not have the brown tinge, but was a very light gray by transmitted light. A solid plate of chromium was polished with pitch and rouge. The resulting surface was very bright but had many fine holes. The curve for this was practically the same as Curve I.

The curves show that surfaces of chromium are no better reflectors than films of many other metals which are much easier to prepare.

A well-defined minimum is noted at 2400, and a maximum at 2150 A. The alloy stellite also shows this same minimum and maximum, due no doubt to the presence of the chromium.

Chromium deposits extremely slowly and it was found difficult to obtain clean white deposits. The best films were obtained by sputtering in an atmosphere of hydrogen, running the discharge for a minute, and then allowing the cathode to cool for a few minutes. It required a week of such treatment to produce an opaque film.

Cobalt (Fig. 7).—A piece of rolled sheet cobalt was ground with emery, polished on pitch and rouge, and finally buffed. The surface took a good polish, being very bright, but showed many irregularities and corrugations. The reflecting power was surprisingly high, considering the appearance of the surface. Table II shows the comparison with results obtained by another observer.

Copper (Fig. 4).—The electrolytically plated gold mirror mentioned elsewhere was plated with copper from a solution of copper

cyanide. This was polished with rouge and chamois, giving a bright mirror, free from imperfections. Curve I is for this mirror.

TABLE II

REFLECTING POWER OF COBALT

Wave-Length	Minor Polished Plate	E. O. H. Polished Plate
2313	31.8	42
2573	39.7	45
2749	45.7	48
2981	48.7	50
3467	51.1	53

Measurements were made on two cathodic films of copper deposited on glass, one being more opaque and less red than the other. Both gave Curve II, which shows a more pronounced hump at 2800 A than other observers have recorded. Table III shows the comparison with results of other observers.

TABLE III

REFLECTING POWER OF COPPER

Wave-Length	Hagen and Rubens Polished Plate	Minor Electrolytic	E. O. H.	
			Electrolytic	Cathodic
2313	.....	29.0	29	32
2510	25.9	.....	27	33
2573	.....	27.9	26	34
2749	.....	27.2	28	36
2880	24.3	.....	29	36
2981	.....	26.4	29	35
3050	25.3	.....	29	33
3260	24.9	.....	29	32
3467	.....	31.5	31	33
3570	27.3	.....	33	35

Gold (Fig. 3).—Several films of gold were deposited cathodically on glass. These deposits were very soft, and it was found that the character of the reflecting power changed after the mirror had been allowed to stand for some time in air. Curve I is the result of measurements on two different cathodic films of gold; these differed only in the thickness of the gold deposit, one appearing opaque and

the other quite green by transmitted daylight. They were measured a few hours after being made, and gave the same curve, Curve I, showing that the gold deposit in each case was thick enough to act as an entirely opaque mirror. The curve shows a sharp maximum at 3010 and a minimum at about 3700 A.

A second measurement of the two films two days later gave Curve II, and measurements a month later showed no further change in the curve. It is seen that the maximum in the curve for the older surface is no longer as sharply defined.

An electrolytic gold mirror was made by depositing gold from a solution of gold cyanide on a speculum mirror. This deposit was rubbed with rouge and chamois, and a bright surface free from scratches was obtained. The curve for this mirror, when new, was practically the same as the curves for the old cathodic films. Unfortunately this mirror was not kept; hence its behavior with time was not recorded.

The records for gold given by other observers do not agree with each other or with the values obtained in the present work. Table IV shows the comparison between the results of the various observers. Hagen and Rubens have not described how their mirror

TABLE IV

REFLECTING POWER OF GOLD

WAVE-LENGTH	HAGEN AND RUBENS	MEIER	E. O. H.	
			Curve I	Curve II
2570.....	38.8	27.6	25	25
2750.....	.....	27.5	29	29
3050.....	31.8	30.4	40	33
3260.....	28.6	35.1	32	30
3570.....	27.9	37.7	30	29

was made. Meier measured a mirror of gold deposited electrolytically, and in his paper (*loc. cit.*) called attention to the fact that he did not find any indication of the minimum in the curve of reflecting power which Hagen and Rubens record at 3570 A.

Lead (Fig. 5).—This was found to sputter quite readily, the same precautions being necessary as were mentioned in the case of cad-

mium. The films are very soft, but come down bright; they soon tarnish. The curve is for an opaque film.

Magnalium (Fig. 7).—It was not found possible to produce a good mirror of this alloy. The specimen was a piece of the alloy made in this laboratory, 69 per cent aluminum and 31 per cent magnesium. The surface finally measured had many pits and scratches, and did not have a high polish. Table V shows the comparison with other results.

TABLE V

REFLECTING POWER OF MAGNALIUM

Wave-Length	Hagen and Rubens	E. O. H.
2510	67	21
2880	70	30
3050	72	34
3260	75	38
3570	81	45

Magnesium (Fig. 3).—A mirror was made of this metal by buffing and finally polishing with dry rouge and chamois. The resulting surface was bright, but had a number of fine scratches and corrugations.

Molybdenum (Fig. 7).—This was a polished specimen of the metal obtained from the Bureau of Standards. The surface was bright and free from scratches. The curve shows a small minimum at 2500 A.

Nickel (Fig. 3).—A fine mirror of nickel was obtained by first depositing a very thin cathodic film of nickel on glass, and then plating this electrically from a solution of nickel ammonium sulphate. This gave a very clean white opaque film, free from imperfections, and was measured a few hours after being made. The curve shows a well-marked maximum at 2110 A. Table VI shows the comparison with results obtained by other observers.

Palladium (Fig. 5).—This metal was deposited cathodically on glass, but the films thus made were not absolutely white; all showed a dark tinge. Several attempts to produce brighter deposits were unsuccessful, and it was decided that the color was due to the

nature of the metal rather than to an impurity or surface film. The curve is for an opaque film.

TABLE VI

REFLECTING POWER OF NICKEL

Wave-Length	Hagen and Rubens	Minor Electrolytic	E. O. H.
2510.....	37.8	30.9	38
2750.....	.....	37.6	43
3050.....	44.2	39.4	46
3260.....	45.2	40.4	47
3570.....	48.8	41.2	49

Platinum (Fig. 3).—An opaque film of platinum was deposited cathodically on glass. Table VII shows the comparison with results of other observers.

TABLE VII

REFLECTING POWER OF PLATINUM

Wave-Length	Hagen and Rubens	Meier Electrolytic	E. O. H. Cathodic
2510.....	33.8	.....	42
2573.....	.....	37.1	43
2749.....	.....	43.1	46
2880.....	38.8	.....	48
2981.....	.....	47.6	49
3050.....	39.8	.....	49
3255.....	.....	48.9	50
3260.....	41.4	.....	50
3570.....	43.4	.....	51
3611.....	.....	52.4	52

Selenium (Fig. 5).—This was an old mirror of metallic selenium which had been prepared by melting the metal and pouring it on glass. For a complete description of the method see Pfund, *Astrophysical Journal*, **24**, 19, 1906. Table VIII shows the comparison with other results.

Silicon (Fig. 6).—A solid piece of silicon was ground with emery and finally polished with pitch and rouge. The resulting mirror was full of pits and had a number of coarse scratches. However, it possessed a remarkably high reflecting power.

A polished specimen of silicon from the Bureau of Standards was measured, and between 3000 and 2000 A it showed a reflecting power of 76 per cent (Curve I). The mirror was slightly convex and had a number of holes and scratches. A special sample of silicon free from holes was obtained from the Carborundum Company, Niagara Falls, and was polished by Dr. Anderson. This mirror gave Curve II. The reason for the difference between the two curves is not known. The two surfaces appeared very much alike; the one of Curve II seemed perhaps to have fewer imperfections.

TABLE VIII

REFLECTING POWER OF METALLIC SELENIUM

Wave-Length	Meier	E. O. H.
2573	23.3	21
2749	25.3	24
2981	31.8	28
3255	32.5	28
3570	30.3	30

Curve III is for an opaque cathodic film of silicon. The deposit was beautifully bright; its reflecting power for visible light more nearly approached that of fresh silver than any of the other metals investigated. In the ultra-violet it is seen that its reflecting power is somewhat inferior to that of the polished specimen of silicon.

The sputtering from the silicon cathode was performed in an atmosphere of mercury vapor, an aluminum anode being used, and it is quite possible that the silicon films contained aluminum. The curve (Curve III) for such a film also points to the possibility of the presence of aluminum, it being lower in the shorter wave-lengths and higher in the longer wave-lengths than the curve for pure silicon. Subsequent experiment indicated that the percentage of aluminum present in these films was small.

Silver (Fig. 4).—A chemically deposited film of silver on glass, polished with rouge and chamois, was measured. The film was opaque, and was measured about a day after being prepared (Curve I). A three-quarter film of silver, showing a dark

gray-blue by transmitted light, gave Curve II. Table IX shows the comparison with other observers.

TABLE IX

REFLECTING POWER OF SILVER

WAVE-LENGTH	HAGEN AND RUBENS		MINOR	E. O. H. CURVE I
	Fresh	Old		
2263	.....	.....	18.4	32
2313	.....	.....	19.9	33
2500	.....	.....	25.0	33
2510	24.1	17.6	25.0	33
2880	21.2	14.5	19.0	25
3050	9.1	11.2	11.6	17
3160	4.2	5.1	4.2	6
3260	14.6	8.0	9.1	18
3380	55.5	41.1	61.7	49
3570	74.5	55.7	75.3	67

Speculum (Fig. 7).—Knowledge of the reflecting power of this alloy, 68.2 per cent copper and 31.8 per cent tin, is of particular interest because Rowland diffraction gratings are ruled almost universally on speculum. Curves I, II, and III illustrate the behavior of a speculum metal surface exposed to air. These curves were obtained from measurements on the same mirror. This mirror had a fine surface free from imperfections; it was freshly polished on pitch and rouge and was measured immediately, giving Curve I. Curve II was taken three days later; Curve III was taken seven days after the initial polishing. Table X shows the comparison with other observations.

TABLE X

REFLECTING POWER OF SPECULUM

Wave-Length	Hagen and Rubens	E. O. H. Curve I
2510	29.9	37
2880	37.7	41
3050	41.7	44
3570	51.0	60

In this laboratory, gratings are ruled entirely on speculum metal. It is the practice before ruling to polish the surface afresh on pitch

and rouge; hence a newly ruled grating finds itself in the condition of the mirror of Curve I. In subsequent use the grating either is never touched again, or at best is merely cleaned with chalk and alcohol. In order to find out definitely the efficiency of the usual grating, Curves IV and V were drawn; Curve V is for an old speculum mirror, with a surface highly polished but covered with a white film of tin oxide; Curve IV is for the same mirror after being cleaned with chalk and alcohol, all visible trace of the oxide being removed. Both curves show a lamentably low reflecting power, and this is undoubtedly due to the presence of the oxide film, which either is not entirely removed by the cleansing process, or immediately forms again.

These results show that there are possibilities for great improvement in the effectiveness of the grating for investigations in the ultra-violet. Depositing a thin layer of platinum or nickel on a speculum grating would increase its efficiency in the ultra-violet two or three times, and a layer of silicon would increase it as much as six times; it is planned to develop a method for doing this. Furthermore, the effect of a thin deposit on the lines of the ruled surface is to increase the brightness of the first order at the expense of the other orders. This is an additional advantage in all work in which the first order is the only one used, as in Lyman's investigation of the Schumann region and in the work recorded in this paper.

The behavior of a speculum surface in the Schumann region is unknown, but it is difficult to believe that the reflecting power experiences a marked increase in this region. That a grating yields such successful results as were obtained by Lyman in his photographic work in the region beyond 1800 A is surprising in view of the present record of the reflecting power of speculum.

Steel (Fig. 5).—The steel mirror was an old one of hardened steel, taken from a tuning fork. It had a fine polish with no imperfections, and was cleaned with chalk and alcohol. The comparison with other observations is shown in Table XI.

Stellite (Fig. 5).—The mirror was a polished specimen of the alloy obtained from the Stellite Works, Kokomo, Indiana. The mirror had a fine polish with no scratches. Stellite is an alloy of chromium and cobalt with impurities; the exact composition is a

commercial secret. As was mentioned under chromium, the curve for stellite shows a maximum at 2150 and a minimum at 2400 A, as do the chromium curves.

TABLE XI

REFLECTING POWER OF STEEL

Wave-Length	Hagen and Rubens Unhardened	Minor	E. O. H. Hardened
2265	.....	34.8	35
2313	.....	35.7	36
2510	32.9	38.9	38
2880	35.0	42.1	44
3050	37.2	42.9	44
3260	40.3	44.8	45
3570	45.0	50.8	50

Tantalum (Fig. 7).—This was a polished specimen of the metal, but the surface finally measured, while having a high polish, was marred by fine scratches. The sample was obtained from the Bureau of Standards.

Tellurium (Fig. 3).—This was a cathodic mirror from the Bureau of Standards. The film was opaque, bright, and free from scratches; it was rubbed with rouge and chamois before measuring.

Tin (Fig. 7).—An opaque surface of tin was deposited cathodically on glass. The mirror was bright and free from imperfections, but was measured three days after being made. It is likely that the surface became very quickly covered with a layer of oxide, which reduced the reflecting power materially. The oxide made its appearance unmistakably in a few days, appearing as a white film.

Tungsten (Fig. 6).—The piece examined was a polished specimen of the metal obtained from the Bureau of Standards. The surface had a good polish, but was marred by a few holes and fine scratches; it was rubbed with rouge and chamois before measuring.

Zinc (Fig. 7).—Bright films of zinc were obtained by sputtering in an atmosphere of hydrogen. The curve is for a three-quarter

opaque film. Table XII shows the comparison with results obtained by another observer.

TABLE XII

REFLECTING POWER OF ZINC

Wave-Length	Meier Polished Plate	E. O. H. Cathodic
2573	20.5	40
2749	47.6	44
2981	60.2	48
3255	68.2	51
3611	70.5	52

DISCUSSION OF RESULTS

The curves show two general characteristics: (1) in the region of the spectrum covered in this investigation the reflecting power decreases as the wave-length decreases; and (2) the reflecting power is never zero. A number of the curves have another characteristic in common. Beyond wave-length 2000 A many of them take a well-defined steeper slant; that is, the reflecting power begins to decrease much more rapidly. That this effect is due to some peculiarity of the apparatus is improbable, for the deflections in this region are very large, and the determination of the reflecting power is accurate even for quite low values of the reflecting power. Furthermore, a number of the substances do not show this rapid falling off in reflecting power. It may be that this observed decrease in reflecting power is a genuine property of the metal, or it may be that the air in contact with the reflecting surface plays an important part. Air has a strong absorption band which begins at 1630 A, and marked absorption starts to set in at 1900 A. It is possible that the optical constants of air begin to change rapidly from wave-length 2000 A down as the absorption band is neared, and this rapid change in the optical properties of the layer of air on the surface of the metal may cause a marked change in the reflecting power of the metal.

A certain similarity exists in the curves for copper, chromium, nickel, cathodic silicon, and molybdenum, for they all show a shallow minimum, i.e., a region of lower reflecting power, in approxi-

mately the same region of the spectrum. There is no evident cause to which this may be attributed. That it is due to the presence of some common impurity is improbable, because the methods of preparation of these five mirrors differed widely.

The one general conclusion that follows from the results of this investigation is that for the metals the reflecting power decreases as the wave-length of the light decreases. Whether this same relation continues to hold for wave-lengths beyond 1800 A in the Schumann and Lyman regions, can be determined only by future experiment. Metals, then, have a maximum reflecting power in the visible and infra-red regions of the spectrum, and it is concluded that the reflecting power diminishes on the short wave-length side of this maximum with no indication of ever increasing again.

Silicon is the one exception to the foregoing conclusion; the reflecting power rises to 76 per cent at 3000 A, remains practically constant from 3000 to 2000 A, and then beyond 2000 drops rapidly, reaching a value of 62 per cent at 1870 A. Future work may show that this rapid decrease beyond 2000 A continues until a low reflecting power is reached, and, if this be so, the elevation in the curve is a region of selective reflection.

Silicon differs from platinum, copper, etc., in that it is a poor conductor of electricity; it is a so-called "metalloid." The behavior of silicon suggests that perhaps there is a class of substances which have the maximum reflecting power in the extreme ultraviolet, just as the true metals show a maximum in the region of the spectrum of longer wave-length. None of the other substances of the metalloid class which were investigated, such as carbon, antimony, etc., show characteristics similar to silicon, and perhaps silicon is unique in this respect.

From a practical standpoint the curves show that from all the metals investigated (with the exception of silicon) two may be selected as being the most serviceable for use in work requiring the reflection of light of short wave-lengths: platinum and nickel. Optical surfaces of these two metals may be readily prepared by cathodic sputtering and by electroplating; these surfaces are quite hard, are slow to tarnish in air, and are not acted on by most of the common laboratory reagents.

Those metals which oxidize easily should be avoided. The appearance of a white or cloudy film on the surface is almost a sure sign of a very low reflecting power in the ultra-violet; on the other hand, the good ultra-violet reflectors give very clear white or bluish-white reflections in visible light.

In this connection silicon again deserves special mention. This metal possesses in a marked degree all the physical properties essential for a perfect reflecting surface; it is as hard as ordinary glass without being brittle; it is not attacked by weak or strong acids, and of course does not tarnish in air; at ordinary temperatures the only reagent which acts on silicon is concentrated potassium (or sodium) hydroxide. The metal takes a high polish by the ordinary method of polishing with pitch and rouge, and brilliant deposits of silicon can be obtained by cathode sputtering, as has been brought out in this investigation. The reflecting power of a silicon mirror was found to be 76 per cent in the region from 2000 to 3000 A (see silicon, Curve I, Fig. 6). The same mirror has been measured by Coblentz[1] in the region of longer wave-lengths, and its reflecting power in the green was found to be 34 per cent, dropping to 28 per cent in the infra-red. Hence a silicon mirror, or grating, possesses a high efficiency throughout the entire range of the spectrum, and the advantages of its use in optical instruments are obvious. Thin films of silicon on interferometer plates will undoubtedly enable investigations in this field to be extended down to 2000 A.

The preparation of mirrors and gratings upon silicon plates depends only upon the possibility of procuring large plates of the metal which are homogeneous; for all the large specimens examined have been found to be porous, and hence are not suitable for the best results. The task of casting silicon pure and in a homogeneous state is certainly not an insurmountable one, and is a problem for the commercial laboratory rather than for the scientific investigator.

SUMMARY

An ultra-violet spectrograph has been set up in which a sodium photo-electric cell connected to an electrometer serves to measure

[1] *Bull. Bureau of Standards*, 7, 217, 1911.

the intensity of the light. With this the reflecting powers of twenty-eight metallic mirrors have been examined; namely, Al, Sb, Bi, Cd, C, carborundum, Cr, Co, Cu, Au, Pb, magnalium, Mg, Mo, Ni, Pd, Pt, Se, Si, Ag, speculum, steel, stellite, Ta, Te, Sn, W, Zn.

The curves of reflecting power have been drawn throughout the region 1800 to 3800 A, and it has been shown that the reflecting power for light of wave-lengths shorter than 3000 A is rarely above 50 per cent, with one noteworthy exception, silicon, which shows a reflecting power of 76 per cent in the region 2000 to 3000 A.

It has been shown that brilliant opaque films of silicon can be prepared by cathode sputtering.

In conclusion I wish to express my hearty thanks to Professor Ames for his interest throughout the course of the work.

Dr. Pfund has been especially helpful; it was at his suggestion that the work was undertaken, and his advice and assistance at every stage have been invaluable. I am deeply indebted to Dr. Anderson for his kindly interest and many helpful suggestions.

Dr. W. W. Coblentz, of the National Bureau of Standards, has kindly allowed the use of several mirrors of the more uncommon metals.

JOHNS HOPKINS UNIVERSITY
June 1915

BIOGRAPHICAL NOTE

Edward Olson Hulburt, son of Lorrain Sherman Hulburt and Elizabeth (Dorey) Hulburt, was born in Vermilion, South Dakota, on October 12, 1890. His early training was received in Baltimore. In 1907 he entered the Johns Hopkins University, and in 1911 was admitted to the degree of Bachelor of Arts. He was Hopkins Scholar for the years 1907–8 and 1910–11. During the year 1911–12 he taught mathematics at the Jefferson School of Baltimore, and in October, 1912, entered the Johns Hopkins University as a graduate student, making physics the principal subject, celestial mechanics and astronomy the first subordinate, and mathematics the second subordinate. He attended graduate courses given by Professors Ames, Wood, Whitehead, Anderson, and Cohen. During the year 1912–13 he was laboratory assistant to Dr. Bliss, and during the years 1913–14 and 1914–15 he was lecture assistant to Professor Ames.